

Key words: line profiles – Sun: photosphere – Sun: chromosphere

Can the temperature of Ellerman Bombs be more than 10000K?

C. Fang^{1,2,3}, Q. Hao^{1,2,3}, M. D. Ding^{1,2,3} and Z. Li^{1,2,3}

¹ School of Astronomy and Space Science, Nanjing University, Nanjing 210093, China;
fangc@nju.edu.cn

² Key Laboratory of Modern Astronomy and Astrophysics (Nanjing University), Ministry of Education, China;

³ Collaborative Innovation Center of Modern Astronomy and Space Exploration

Abstract Ellerman bombs (EBs) are small brightening events in the solar lower atmosphere. By original definition, the main EB’s characteristic is the two emission bumps in both wings of chromospheric lines, such as $H\alpha$ and Ca II 8542 Å lines. Up to now, most authors found that the temperature increase of EBs around the temperature minimum region is in the range of 600K-3000K. However, with recent IRIS observations, some authors proposed that the temperature increase of EBs could be more than 10000K. Using non-LTE semi-empirical modeling, we investigate the line profiles, continuum emission and the radiative losses for the EB models with different temperature increases, and compare them with observations. Our result indicates that if the EB maximum temperature attains more than 10000K around the temperature minimum region, then the resulted $H\alpha$ and Ca II 8542 Å line profiles and the continuum emission would be much stronger than that of EB observations. Moreover, due to the high radiative losses, the high temperature EB would have a very short lifetime, which is not comparable with the observations. Thus, our study does not support the proposal that the EB temperatures are higher than 10000K.

1 INTRODUCTION

Ellerman bombs (EBs: Ellerman 1917) are small-scale brightening events in the solar lower atmosphere. Their characteristic feature is the excess emission in the wings of chromospheric lines, such as $H\alpha$ and Ca II 8542 Å lines. Using high spatial resolution data, it was found that the lifetime of EBs is 2-20 minutes, and their size can be smaller than 1'' (Vissers et al. 2012; Nelson et al. 2013; Li et al. 2015). The temperature increase of EBs around the temperature minimum region (TMR) is about 600-1500 K (Georgoulis et al. 2002; Fang et al. 2006; Hong et al. 2014; Berlicki et al. 2014). Recently, using high-resolution $H\alpha$ and Ca II 8542 Å spectra obtained by the 1.6m New Solar Telescope (NST), Li et al. (2015) found that the temperature increase can be about 3000 K even for three smallest EBs. The energy of EBs is estimated to be in the range of $10^{25} - 10^{27}$ ergs (e.g. Georgoulis et al. 2002; Fang et al. 2006; Li et al. 2015). It should be emphasized that there are some “pseudo-EBs”, being bright points in some images, but probably manifestations of deep radiation escape (Rutten et al. 2013; Vissers et al. 2015). Thus, the best way to identify EBs is using spectral data.

Recently, with the Interface Region Imaging Spectrograph (IRIS; De Pontieu et al. 2014), some authors found that there are small-scale bright regions observed in the 1400 Å and 1330 Å images, called IRIS bombs (IBs) (Peter et al. 2014; Tian et al. 2016), which have a local heating in the photosphere up to $\sim 8 \times 10^4$ K under the assumption of collisional ionization equilibrium (Peter et al. 2014) or 1-2

$\times 10^4$ K under the local thermodynamic equilibrium (LTE) assumption (Rutten et al. 2016). Thus, the relationship between the EBs and IBs becomes an interesting question. Vissers et al. (2015) studied five EBs and found that strong EBs can produce IB-type spectra. Kim et al. (2015) also found the connection between an IB and an EB. Recently, Tian et al. (2016) used IRIS and the Chinese New Vacuum Solar Telescope (NVST; Liu et al. 2014) data, and identified 10 IBs. Among them, 3 are obviously and 3 others are possibly connected to EBs, and the remaining four IBs are not EBs. They concluded that some EBs connected to IBs can be heated to $1\sim 8 \times 10^4$ K, which is much hotter than that obtained from non-LTE modeling of EBs. Thus, whether EBs can be heated to such a high temperature is a hot topic.

In this paper, we use non-LTE modeling to investigate some characteristics of EB models with different temperatures, and compare them with observations, which were performed with the largest aperture solar telescope in the world, the 1.6 meter off-axis New Solar Telescope (NST) (Goode et al. 2012; Cao et al. 2010) at the Big Bear Solar Observatory (BBSO). The method of non-LTE modeling is described in Section 2. The resulted characteristics of EB models are given in Section 3. General discussion and conclusion are given in Section 4.

2 SEMI-EMPIRICAL MODELING OF EB MODELS WITH DIFFERENT TEMPERATURES

We use the non-LTE method as described in the paper of Fang et al. (2006). That is, prescribing a semi-empirical temperature distribution of an EB model, we solve the statistical equilibrium equation, the radiative transfer equation, the hydrostatic equilibrium, and the particle conservation equations iteratively. A four-level hydrogen atom and a five-level Ca II atom are taken. All the bound-free and the free-free transitions of the hydrogen atom and negative hydrogen (H^-) are included. The converging criteria is that the relative difference of the mean intensities between the last two iterations is less than 10^{-7} and 10^{-9} for hydrogen and calcium atoms, respectively. Then the $H\alpha$ and Ca II 8542 Å line profiles and continuum intensity can be calculated.

As the typical cases, we take three EB models with different temperatures around the TMR. The models labeled EB15000 and EB10000 have a maximum temperature of 15000K and 10000K, respectively. The third one labeled EB0955 has a maximum temperature of 7000K, which is about the same as that given by the empirical model labeled No.2 EB in our recent paper of Li et al. (2015). The empirical model of EB0955 can well reproduce the $H\alpha$ and Ca II 8542 Å line profiles observed by the Fast Imaging Solar Spectrograph (FISS) (Chae et al. 2013) of BBSO/NST on 2013 June 6 at 09:55 UT. Compared with the VALC quiet-Sun model (Vernazza et al. 1981), the temperature increases for the three EB models are 11000K, 6000K, and 3000K, respectively.

Figure 1 gives the temperature distributions for the three models. For comparison, we also plot the temperature distributions in the semi-empirical model for plages (denoted by “Plage”) given by Fang et al. (2001) and for the VALC quiet-Sun model (denoted by “VALC”). In the figure, M is the column mass density.

Figure 2 gives both the observed and computed $H\alpha$ and Ca II 8542 Å line profiles for the three EB models. It can be seen that the computed profiles of the EB0955 can well match the observed ones, while that of the EB10000 and EB15000 are much stronger and broader than that given by observations.

Using the non-LTE method mentioned above, we can calculate the continuum emission for the three models. Figure 3 gives the result. It can be seen that the continuum emissions of the EB10000 and EB15000 are much stronger than that of the EB0955. Particularly, there would be a very strong Balmer jump for both EB10000 and EB15000. Obviously, such strong continuum emissions and very strong Balmer jump are never observed in EB’s spectra.

3 RADIATIVE LOSSES

We can further estimate the radiative losses of the three EB models by using the non-LTE modeling. The method is similar to that in Fang et al. (2006). That is, considering that the main heating regions of three EB models are around the TMR, we can use the following equation to estimate the total radiative losses E_r of the EB models:

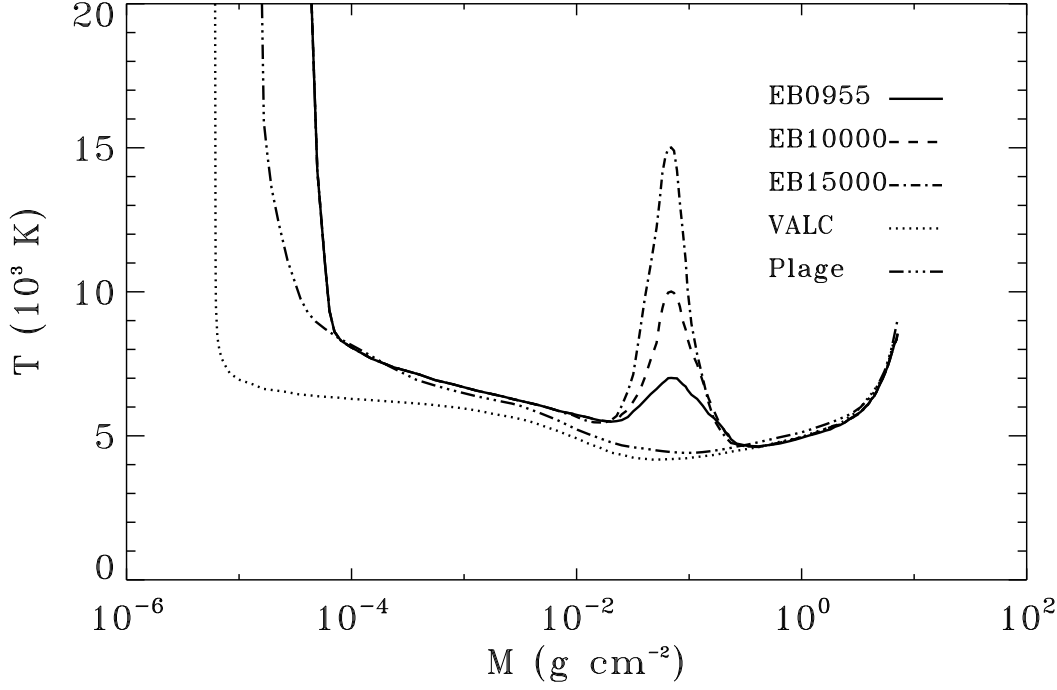


Fig. 1 Temperature distributions in the three EB models: EB0955 (*solid line*), EB10000 (*dashed line*) and EB15000 (*dashed-dotted line*), compared to that of the plage model (*dashed three-dotted line*) given by Fang et al.(2001), and that of the quiet-Sun model (i.e., the VALC model, *dotted line*) given by Vernazza et al.(1981).

$$E_r = DA_{EB} \frac{R_{EB}}{4}, \quad (1)$$

where

$$R_{EB} = \int_{h_1}^{h_2} R_r dh$$

is the height-integrated radiative cooling rate per unit area in the main heating region $[h_1, h_2]$. h_1 and h_2 are the lower and the upper heights of the heated region, respectively. R_r is the peak rate of radiative losses in units of $\text{erg cm}^{-3} \text{s}^{-1}$. Considering that the rate of radiative losses changes during the EB lifetime D , we take 1/4 of the peak value as the mean rate. A_{EB} is the area of the EB. We use the empirical formula given by Jiang et al.(2010), which is a modification of the formula of Gan et al.(1990) and is more suitable for the small-scale activities. It is given as follows:

$$R_r = n_H n_e (\alpha_1(h) + \alpha_2(h)) f(T), \quad (2)$$

where

$$\log \alpha_1(h) = 1.745 \times 10^{-3} h - 4.739,$$

$$\alpha_2(h) = 8.0 \times 10^{-2} e^{-3.701 \times 10^{-2} h},$$

$$f(T) = 4.533 \times 10^{-23} (T/10^4)^{2.874},$$

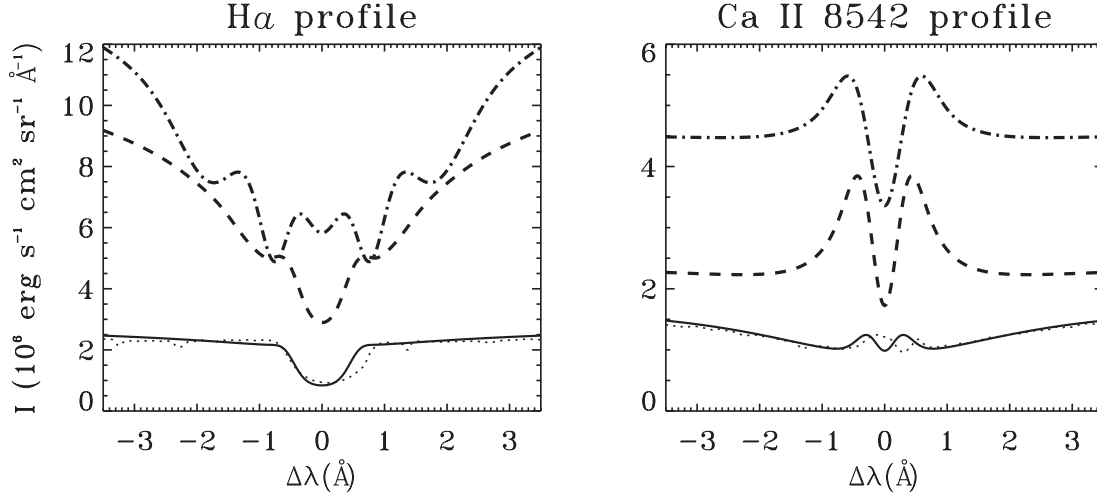


Fig. 2 Comparison between the observed (*dotted lines*) and computed H α and Ca II 8542 Å line profiles for the EB0955 (*solid lines*), the EB10000 (*dashed lines*) and the EB15000 (*dashed-dotted lines*). All theoretical profiles are convolved with a macroturbulence velocity of 8 km s^{-1} .

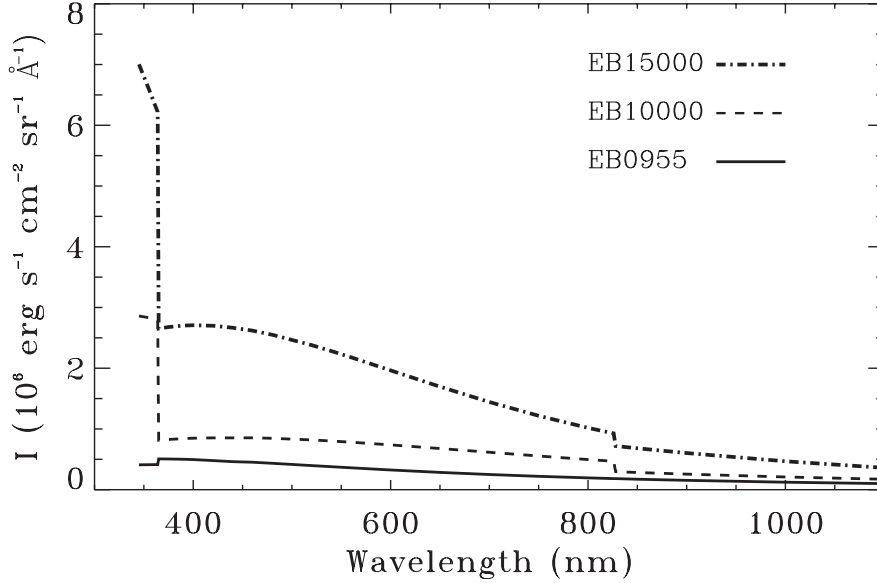


Fig. 3 Continuum emissions for the three EB models.

where h is the height in kilometer. Thus, using the non-LTE calculation results, we can obtain the radiative losses for the three EB models. Figure 4 gives the result. It is clear that the radiative losses of the EB10000 and EB15000 are about two or three orders of magnitude higher than that of the EB0955. This is due to their very high electron density in the lower atmosphere, which is caused by photoionization produced by high Balmer and Paschen emissions in the EB region, as shown in Figure 3.

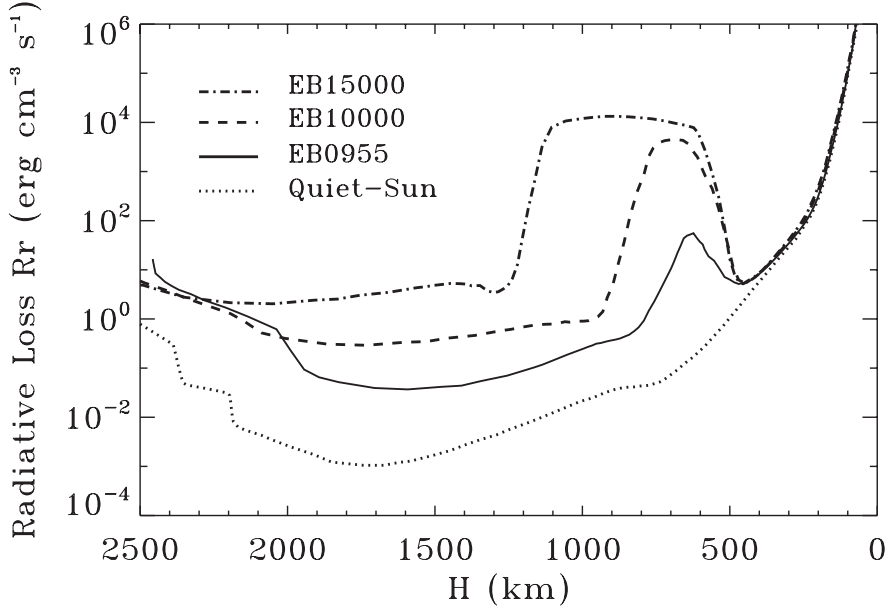


Fig. 4 Peak radiative losses for the three EB models.

Table 1 Characteristics for the three EB models

EB	Assuming size ($x \times y$) (arcsec)	T_{max} (K)	R_{EB} ($\text{erg cm}^{-2} \text{s}^{-1}$)	Lifetime (s)
EB0955	0.5×0.5	7000	8.21×10^8	371
EB10000	0.5×0.5	10000	7.26×10^{10}	4.19
EB15000	0.5×0.5	15000	6.08×10^{11}	0.50

Further, if assuming that the main mechanism of the energy losses is the radiative one, and taking the e-folding time of the maximum temperature decreasing as the lifetime of the EBs, then, for a given energy E of an EB, we can estimate its lifetime by the formula:

$$D = \frac{4 \times E}{A_{EB} R_{EB}}. \quad (3)$$

From the non-LTE calculation, we can obtain all necessary quantities for estimating the durations of the three EB models. For comparison, we assume that all the EBs have the typical size of EBs being $0''.5 \times 0''.5$. We take $h_1 = 337$ km, and $h_2 = 2044$ km for all three EBs. Considering the rapid decrease of the hydrogen density with height, we neglect the contribution from the higher layers.

We take the total radiative energy $E = 1 \times 10^{26}$ ergs, which is a typical value for an EB (e.g. Fang et al. 2006; Li et al. 2015). Using Eq. (3), we can estimate the lifetimes of the three EBs, which are listed in Table 1. It can be seen that the lifetimes of EB10000 and EB15000 would be two or three orders of magnitude shorter than the EB0955, due to their very high radiative losses, and are not comparable with observations. Of course, for some very bright EBs the total radiative energy could be higher, say, 1×10^{27} ergs. In this case, the lifetimes of the high-temperature EBs are still very short. Moreover, for an EB having high temperature, the energy losses by heat conduction should be considered. It will decrease the EB lifetime further.

4 DISCUSSION AND CONCLUSION

Using non-LTE theory, we calculate the $H\alpha$ and Ca II 8542 Å line profiles, as well as the continuum emissions, for three EB models with different temperatures around the TMR. Our results clearly reveal that the EB models with the maximum temperature over 10000K will produce not only much stronger $H\alpha$ and Ca II 8542 Å line profiles, but also very strong continuum emissions, particularly in the Balmer continuum. These line profiles and continuum emissions are not comparable with an EB model denoted as EB0955, which reproduces well the observations by BBSO/NST on 2013 June 6 at 09:55 UT. It should be emphasized that all these characteristics produced from EB10000 and EB15000 are never reported in EB spectral observations. Moreover, as mentioned above, we regard the e-folding time of the EBs as its lifetime, and the calculation is approximate since the radiative cooling rate changes non-linearly with temperature. Nevertheless, our results at least indicate that an EB with a temperature increase over 10000 K around the TMR, if actually produced, cannot persist enough long with its high-temperature character. This is certainly not matching the EB observations. In a word, it is unlikely that the maximum temperature of EBs around the TMR could exceed 10000K. We notice that recently Reid et al. (2017) used RADYN 1-dimensional radiative transfer code and got the conclusion that the presence of superheated regions in the photosphere ($>10,000$ K) is not a plausible explanation for the production of EB signatures. It is consistent with our result.

It is thought that magnetic reconnection in the photosphere or lower chromosphere could be a mechanism for EBs (Ding et al. 1998; Georgoulis et al. 2002; Fang et al. 2006; Pariat et al. 2007; Isobe et al. 2007; Watanabe et al. 2011; Yang et al. 2013; Nelson et al. 2013). We have performed two-dimensional numerical MHD simulations on the magnetic reconnection in the solar lower atmosphere (Chen et al. 2001; Jiang et al. 2010; Xu et al. 2011). Our results indicated that magnetic reconnection in the lower solar atmosphere can explain the temperature enhancement of about 600-3000 K and the lifetime of EBs. Recently, Ni et al. (2016) performed 2.5 dimensional MHD simulation and indicated that both the high temperature ($\geq 8 \times 10^4$ K, if the plasma β is low) and low temperature ($\sim 10^4$ K, if β is high) events can happen around the TMR. However, they did not include the non-equilibrium ionization effect, which is certainly important for the high temperature case (Chen et al. 2001). Nevertheless, their result implies that the high and low temperature events can not happen at the same place. It is true that IBs need a high temperature of over 10000 K to explain the enhanced EUV lines. However, according to our result, the maximum temperature of EBs around the TMR is unlikely higher than 10000 K. This implies that IBs and EBs are unlikely to happen at exactly the same place. There are indeed some IBs that are closely connected to EBs in observations (e.g., Tian et al. 2016). They may reflect different temperature components that are produced by a common magnetic reconnection process. In fact, previous numerical simulations have revealed that both low and high temperature components can exist in the case of emerging flux reconnecting with pre-existing magnetic field (Yokoyama et al. 1995; Jiang et al. 2012). Another possibility is that the jets produced by some EBs (see e.g. Nelson et al. 2015) could heat the upper atmosphere via waves or shocks. In this case, the high temperature region would be higher than the low temperature one. Then the apparent coincidence of both phenomena could only be due to the project effect. For checking this point, a coordinated observation between IRIS and a large-aperture ground-based telescope in a region close to the limb may be useful. Anyway, for a clearer explanation of the relationship between EBs and IBs, we need more observations with higher spatial and temporal resolutions in the future.

Based on the analysis of the three EB models, we draw the conclusion as follows:

According to our results of non-LTE calculation and semi-empirical modeling, it is unlikely that the maximum temperature of EBs around the TMR could exceed 10000K, otherwise the resulted $H\alpha$ and Ca II 8542 Å line profiles, as well as the continuum emissions, would be too strong to be comparable with the EB observations. Particularly, due to very high radiative losses in the high temperature models (EB10000 and EB15000), the lifetime of these events would be very short, which is inconsistent with any EB observations.

Acknowledgements We thank a lot to the anonymous Referee for his/her valuable suggestions. This work is supported by the National Natural Science Foundation of China (NSFC) under the grants 11533005, 11025314, 13001003, 11203014, 11103075 as well as NKBRSF under grants 2014CB744203.

References

- Berlicki, A., & Heinzel, P. 2014, *A&A*, 567, A110
- Cao, W., Gorceix, N., Coulter, R., et al. 2010, *Astronomische Nachrichten*, 331, 636
- Chae, J., Park, H.-M., Ahn, K. et al. 2013, *Sol. Phys.*, 288, 1
- Chen, P. F., Fang, C., & Ding, M. D. 2001, *ChJAA*, 1, 176
- De Pontieu, B., Title, A. M., Lemen, J. R., et al. 2014, *Sol. Phys.*, 289, 2733
- Ding, M. D., Hénoux, J. -C., & Fang, C. 1998, *A&A*, 332, 761
- Ellerman, F. 1917, *ApJ*, 46, 298
- Fang, C., Hénoux, J. C., & Gan, W. Q. 1993, *A&A*, 274, 917
- Fang, C., Ding, M. D., Hénoux, J.-C., & Livingston, W. C. 2001, *Science in China, Ser. A*, 44, 528
- Fang, C., Tang, Y. H., Ding, M. D. & Chen, P. F. 2006, *ApJ*, 643, 1325
- Gan, W. Q., & Fang, C. 1990, *ApJ*, 358, 328
- Gary, G. A. & Hagyard, M. J. 1990, *Sol. Phys.* 126, 21
- Georgoulis, M. K., Rust, D. M., Bernasconi, P. N., & Schmieder, B. 2002, *ApJ*, 575, 506
- Goode, P. R., & Cao, W. 2012, *Proc. SPIE*, 8444, 3
- Gregal J. M. Vissers, Luc H. M. Rouppe van der Voort, & Robert J. Rutten. 2013, *ApJ*, 774, 32
- Hashimoto, Y., Kitai, R., Ichimoto, K. et al. 2010, *PASJ*, 62, 879
- Hong, J., Ding, M. D., Li, Y. et al. 2014, *ApJ*, 792, 13
- Isobe, H., Tripathi, D., Archontis, V. 2007, *ApJL*, 657, 53
- Jiang, R. L., Fang, C., & Chen, P. F. 2010, *ApJ*, 710, 1387
- Jiang, R. L., Fang, C., & Chen, P. F., 2012, *ApJ*, 751, 152
- Kim, Y.-H., Yurchyshyn, V., & Bong, S.-C. 2015, *ApJ*, 810, 38
- Li, Z., Fang, C., Guo, Y. et al. 2015, *RAA*, 15, 1513
- Liu, Z., Xu, J., Gu, B.-Z., et al. 2014, *RAA*, 14, 705
- Ni, L., Lin, J., Roussev, I. I., & Schmieder, B. 2016, *ApJ*, 832, 195
- Nelson, C. J., Doyle, J. G., Erdelyi, R. et al. 2013, *Sol. Phys.* 283, 307
- Nelson, C. J., Scullion, E. M., Doyle, J. G. et al., 2015, *ApJ*, 798, 19
- Pariat, E., Schmieder, B., Berlicki, A. 2007, *A&A*, 473, 279
- Peter, H., Tian, H., Curdt, W., et al. 2014, *Sci*, 346, 1255726
- Reid, A., Mathioudakis, M., Kowalski, A., et al. 2017, *arXiv:1701.04213*
- Rutten, R. J., Vissers, G. J. M., Rouppe van der Voort, L. H. M. et al. 2013, *JPhCS*, 440, 012007
- Rutten, R. J. 2016, *A&A*, 590, 124
- Tian, H., Xu, Z., He, J., & Madsen, C. 2016, *ApJ*, 824, 96
- Vernazza, J. E., Avrett, E. H., & Loeser, R. 1981, *ApJS*, 45, 635
- Vissers, G. J. M. & Rouppe van der Voort, L. H. M. 2012, *ApJ*, 750, 22
- Vissers, G. J. M., Rouppe van der Voort, L. H. M., & Rutten, R. J. 2013, *ApJ*, 774, 32
- Vissers, G. J. M., Rouppe van der Voort, L. H. M., Rutten, R. J., et al. 2015, *ApJ*, 812, 11
- Watanabe, H., Vissers, G., Kitai, R. et al. 2011, *ApJ*, 736, 71
- Xu, X. Y., Fang, C., Ding, M. D., & Gao, D. H. 2011, *RAA*, 11, 225
- Yang, H., Chae, J., Lim, E. et al., 2013, *Sol. Phys.*, 288, 39
- Yokoyama, T., & Shibata, K. 1995, *Nature*, 375, 42